# Investigation of Parameter-Property Relationship in Material Extrusion Additive Manufacturing

**Synopsis**

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## INTRODUCTION

Additive manufacturing (AM), also known as prototyping, 3D printing, and freeform fabrication, produces physical goods from digital computer-aided design (CAD) models by depositing, fusing, and hardening materials layer by layer. Other names for this process include freeform fabrication, rapid prototyping, and rapid manufacturing [1]. AM systems provide a fresh method for designing and preparing parts and materials compared to conventional manufacturing techniques like subtractive and constructive production. Since AM systems provide a fresh perspective on the design and production of components and materials, they are ideally suited for high-yield production. But it is well-recognized that the AM procedure is a very sophisticated system that integrates material physics, aerodynamics, aesthetics, and computer science [2]. Understanding the advancements in AM technology necessitates a solid foundation in material science. Researchers in this field have a considerable interest in the creation of novel, 3D printing-applicable materials and with the help of decision support system, the user can set the ME process variable in order to achieve specific build goals and desired part characteristics [3].

## MATERIAL EXTRUSION (ME)

Material extrusion is an additive manufacturing process in which material is forced out of a nozzle under constant pressure. After leaving the nozzle, the filament will settle at a consistent rate and completely harden on the substrate. In addition, the material must bind to the prior material in order for a solid portion to form and remain in place during the process [4]. ME is currently the most popular layer fabrication method. Direct fabrication of final products without the necessity of tooling, dies, or moulds are one of the most significant limitations of traditional manufacturing processes, but this method prevents those limitations through the use of additive manufacturing [5]. This technique is becoming increasingly popular because of its few cycle times, precise features, straightforward interface, and compatibility with a wide range of CAD applications [6]. With its low start-up costs and high throughput, ME has become a popular additive manufacturing method for prototype testing and mass production [7]. Since the last decade, Additive manufacturing has emerged as an efficient tool in new product development and thus tackles the requirements of industries [8]. However, the ME cannot replace the traditional manufacturing processes but is an alternative way to enhance the efficiency of the

fabrication process of complex parts with high dimensional accuracy [9]. ME has been widely used in additive manufacturing technology that provides functional prototypes in various thermoplastics due to its ability to produce complex geometrical parts neatly and safely in an office-friendly environment. ME is now commonly used for modelling, prototyping, and production applications. Figure 1 illustrates the ME process; where the material is melted into liquid state in a liquefier head and then selectively deposited through a nozzle that traces the parts cross sectional geometry to produce 3D parts directly from a CAD model in a layer-by-layer manner [10].

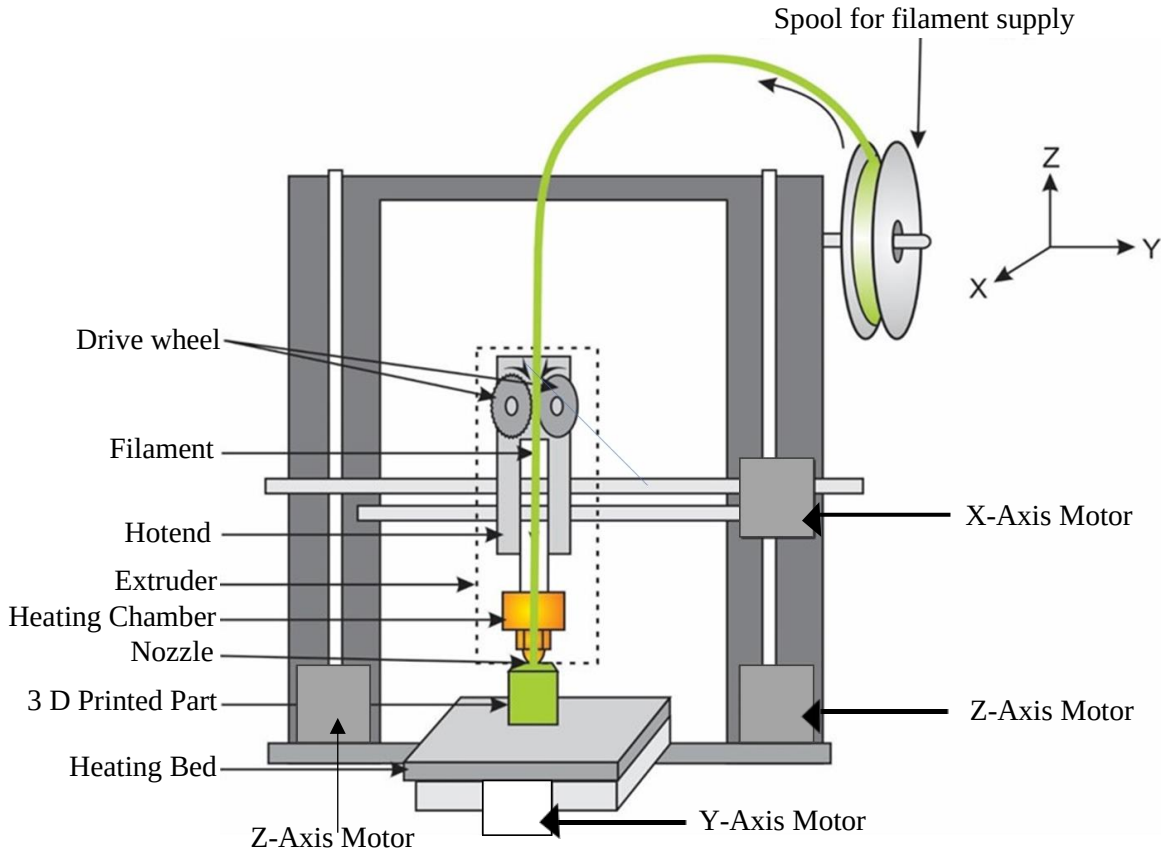


Figure 1 Material Extrusion Additive Manufacturing

**ME PROCESS PARAMETERS**

ME is a complex process that exhibits much difficulty in determining optimal parameters due to the presence of a large number of conflicting parameters that will influence the part quality and material properties. The part quality and mechanical properties of fabricated part can be attributed to proper selection of process parameters [11].

Some main parameters are described as follows:

Build orientation refers to the way in which the part is oriented inside the build platform with respect to X, Y, Z axis [12].

Air gap refers to the gap between adjacent raster tool paths on the same layer. Raster angle refers to the angle of the raster pattern with respect to the X axis on the bottom part layer. Specifying the raster angle is very important in parts that have small curves [13]. The typical allowed raster angles are from 0° to 90°.

Extrusion temperature is the temperature at which the filament of a material is heated during the ME process. Extrusion temperature depends on various aspects, for example, the type of material or print speed [13].

Raster width is the width of the material bead used for raster's. Larger value of raster width will build a part with a stronger interior. Smaller value will require less production time and material. The value of raster width varies based on nozzle tip size [14].

**ME PARTS PERFORMANCE ANALYSIS**

The ME fabricated functional part's performance can be evaluated by investigating the mechanical, physical, electrical properties etc., depending upon the working condition of the component [15]. Among the various properties, dimensional accuracy, tensile strength, compressive strength, surface roughness and wear properties are the significant performance analysis across multiple engineering applications [16]. The three-dimensional printed (3-DP) manufacturing process-based ME technique is developed to fabricate any component using fabrication data from designing software [17]. Since the 3-DP ME process involves various input process parameters, the characteristics of the different parts can be improved by selecting the proper input process parameters [18]. So, there is a requirement for additional headway in these 3-DP techniques by assessing various ME technique fabricated part characteristics, which are primary restraints. Dimensional precision is a significant property for functional parts. Changing the ME input parameter significantly affects dimensional precision. Many scientists have worked widely on input parameters to decide their impact on the dimensional precision of the printed parts [19-23]. The complex process character and incompatible factors of ME make a lot of trouble deciding the input process parameters, which fundamentally influence the accuracy. It is essential to know how a material behaves under loading after fabrication by the ME technique for better

performance. Therefore, it is necessary to be familiar with the mechanical characteristics of any end-use application produced [24].

## LITERATURE REVIEW

In ME, process parameters plays very important part and mechanical properties are greatly affected by them and therefore there is high scope of understanding parameter-property relationships [25]. Kumar et al. [26] analyzed the flexural properties of PLA composites based on infill density, infill speed and demonstrated the importance of surface roughness and surface porosity on mechanical properties. Similar work is also performed by Jayanth et al. [27], but they analyzed flexural strength for variations in printing speed and layer thickness. They demonstrated that flexural strength is enhanced at lower values of layer thickness and printing speed. Another group of researchers [28] investigated flexural strength of PLA specimens for varying layer thickness and nozzle diameters, explaining the dependency of layer thickness on part strength. Li et al. [29] worked on carbon fibre reinforced composites and demonstrated that flexural strength increases by 164% by designing nozzle and path control strategies. In many studies, researchers considered FDM process variables such as layer thickness [30], width, and distance between filaments, nozzle temperature; build orientation [31-33] and material feed rate [34]. Ning et al. [35] investigated the tensile properties of carbon fibre-reinforced plastic composite parts for different filler loadings. They observed that tensile strength increases by 22% for specimen with 5% carbon content. Similar trend is also observed by Es-Said et al. [36] where variations in tensile strength for ABS in different layer orientations is investigated. The anisotropy in the material properties were also examined based on different parameters like infill density, infill pattern, raster orientations indicating variations in tensile and yield strength [37,38]. In recent years, researchers have also started to investigate the surface roughness of 3d printed parts [39-41] through some post-processing methods. With the considerable use of 3D printing in variety of fields, problems associated with the AM has also been identified and worked upon. Due to the unpredictability of the approach and the variety of process factors, various methodologies have been utilized to obtain the optimal ME process parameter setting values. To improve the process, various experimentation procedures has been chosen. The exploratory investigation determined the optimal selection of input components in a significant proportion of the presented research. Ahn, Montero et al. [42] employed factorial design to examine the impression of

distinctive parameters such as build orientation, road width, filament colour, and melting temperature on compressive and tensile behaviour of ABS material parts fabricated by ME. Horvath et al. [43] examined the optimal factor settings for reducing surface roughness in fused deposition modelling FDM prototypes. A two-level, three-factor and three-level, two-factor, full factorial experiment were done, respectively. The factors selected for that study were model temperature, layer thickness, and style of part fill. The outcomes of the two tests were compared to determine the optimal combination of factors for reducing surface roughness.

The optimization and modelling work of various ME conflicting process parameters has been carried out for single-objective and multi-objective using multiple optimization techniques (Wang, Lin et al. 2007 [44], Sood, Equbal et al. 2011 [45], Rayegani and Onwubolu 2014 [46]. Wang et al. used the Taguchi method with the grey relational assessment to investigate the effects of control parameters on the surface quality, including layer height, distributing style, supported style, and deposition orientations. It was determined that a 62.27 % improvement in surface roughness was achieved by employing the optimal factor settings. This research showed that the optimal surface roughness parameter combinations could be determined with fewer experiments utilizing the Taguchi approach than the full factorial design. Nancharaiah et al. [47] also adopted the Taguchi method and the ANOVA analysis to identify the most influential factors on the surface quality of deposited printed components. The input factors were considered, including layer height, raster angle, and air gap. They concluded that the efficiency of FDM parts was greatly impacted by layer height and air gap. However, this study did not examine the best choices for layer thickness, raster angle, or air gap within range. Zhang et al. 2012 [48] developed the Taguchi technique in conjunction with fuzzy comprehensive assessment to develop empirical relations between process parameters such as extrusion velocity, infill velocity, surface finish, and geometric error of FDM-manufactured Acrylonitrile butadiene styrene ABS objects.

Tosto et al. 2022 [49] used a design of experiments (DoE) approach to analyse the relationship between nozzle temperature, layer height, flow rate and the tensile or bending characteristics of sintered 316L steel material. After printing, the morphology and physics of both the original green object and the sintered version were evaluated. The optimal printing parameters were determined using statistical study

and the surface response technique. The specimens' mechanical characteristics improved with increasing flow rate, layer thickness, and decreasing nozzle temperature.

Jain et al. 2022 [50] analysed and compared the mechanical properties of composites made from carbon fibre-reinforced polylactic acid (CF-PLA), graphene-reinforced polylactic acid (Gr-PLA), and multi-walled carbon nanotubes-reinforced polylactic acid (MWCNTs-PLA) using Fused Filament Fabrication. The analysis of the tensile strength's effect on the process parameters using ANOVA and Taguchi's L9 array design of the experiment revealed that the layer height has the greatest effect on the tensile strength of Gr-PLA while the raster angle remains the most crucial factor for both CF-PLA and MWCNTs-PLA. Table 1 details different ME technique-related research in which different statistical approaches optimize the input parameters for enhancing the various part characteristics.

Table 1: Researchers focusing on different optimization approaches to analyse the input parameters and characteristics.

| Reference | Material | Techniques & Methods | Input Process Factors | Part Characteristics |
|---|---|---|---|---|
| Zhang Y and Chou K 2008 | ABS | Central composite design (CCD), ANOVA, Regression, | Raster width, Layer height, Printing speed | Part distortion and Residual stress |
| Panda, Padhee et al. 2009 | ABS | Bacterial foraging optimization (BFO), RSM | Raster orientation, build style, layer height, Raster width, air gap. | Impact, Flexural, and Tensile Strength |
| Sood, Ohdar et al. 2010 | ABS | CCD, ANOVA | Raster orientation, Layer thickness, Build orientation, Air gap, Raster width. | Flexural strength, Impact and Tensile strength |
| Gurrala and Regalla 2014 | ABS | RSM, FCCD, ANOVA | Part orientation, Sliding speed, Normal load. | Friction & Sliding wear behaviour |
| Peng, Xiao et al. 2014 | ABS | RSM, Fuzzy, ANFIS, ANN, GA | Extrusion rate, Filling rate, Layer Thickness, and Line Width Compensation | Errors in measurements, construction time, and warp deformation |
| Torres, Cotelo et al. 2015 | PLA | ANOVA, Regression, Taguchi method | Infill density, Layer thickness, and Post processing | Shear modulus, Yield strength, Fracture strain, Proportional limit, and Ultimate shear strength |
| Ziemian, Okwara et al. 2015 | ABS | ANOVA | Raster angle | Fatigue and Tensile strength |

| | | | | |
|---|---|---|---|---|
| Devika and Gupta, 2016 | PC-ABS | Taguchi method, ANOVA and RSM | Slice height, Raster angle, Air gap, Raster width and Build style | Porosity, Surface finish, and Dimensional accuracy |
| Srivastava, Rathee et al. 2018 | ABS | RSM, Fuzzy methodology | An air gap, Raster angle, Shell width, Build orientation, Road width, and Layer thickness | Supporting volume and Part building time |
| Yadav, Chhabra et al. 2019 | ABS | ANN, GA-ANN | Extrusion temperature, Material, and Infill-density | Tensile Strength |
| Camposeco Negrete 2020 | Acrylonitrile styrene acrylate (ASA) | Taguchi method, Desirability analysis | Infill pattern, Layer height, Build orientation, Printing plane and Position of the piece. | Processing time, Dimensional accuracy, and Energy consumption of the machine |
| Pant, Singari et al. 2022 | PLA | Taguchi method & ANN | Layer thickness, Build orientation, Temperature. | Sliding wear |
| Jain et al. 2022 | PLA Composites | ANOVA & Taguchi method | Layer thickness, Feed rate and Raster angle | Tensile Behavior |

**OBJECTIVE**

The research work will focus on the following objectives:

1. Development of experimental setup for accomplishing the experiments with fabricated specimens through material extrusion additive manufacturing process.
2. Mechanical characterization of developed specimens for creating a dataset for selected target factors.
3. Optimizing parameters for improving the process while considering particular target factors using selected statistical techniques.
4. Experimental validation for different process parameters improves the process while considering particular target factors obtained through selected statistical techniques.

The flow chart of the proposed work is mentioned in the figure 2.

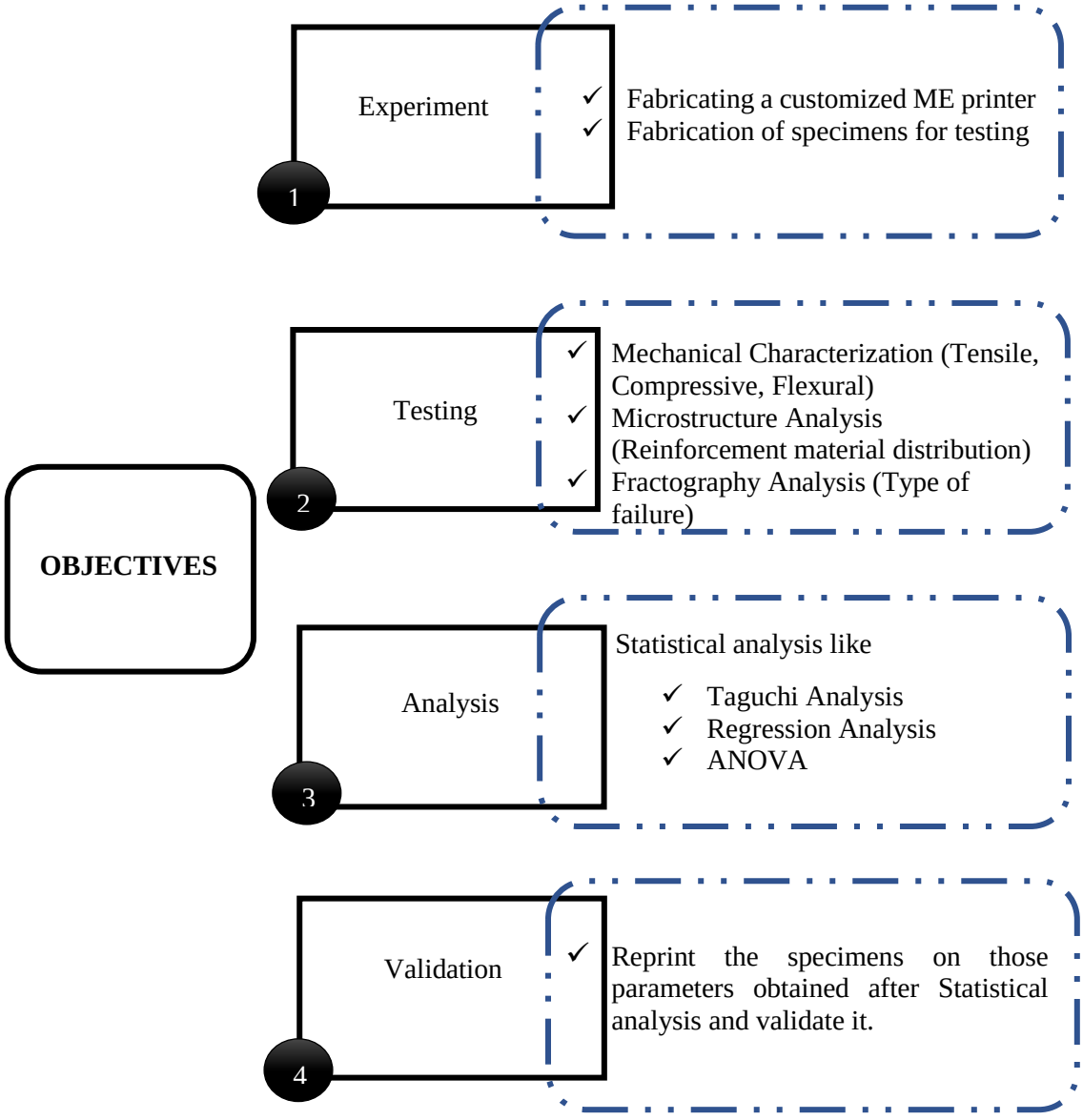


Figure 2 Flowchart of proposed work

**METHODOLOGY**

1. A thorough literature survey of the latest advancements in AM technology for improved understanding and comparative study of the Material Extrusion process using polymer and polymer composites.
2. Study and analysis of 3D printed parts and their process parameters.
3. Experimentation and development of dataset with selected process parameters (like raster angle, feed rate, infill density, layer height, nozzle diameter, bed temperature) and target factor (namely mechanical characterization, surface characterization).

4. Optimizing process parameters for the particular target factor using the selected statistical technique (viz Design of Experiment, ANOVA and Taguchi method).
5. Pilot Scale demonstration of the specimen using manipulated process parameters for a particular target factor.

**EXPECTED OUTCOMES**

1. The proposed research and experimental studies will lead to the development of an experimental setup.
2. An effort has been made to investigate the effects of process parameters on mechanical and electrical characterization.
3. The proposed work will enable the method for obtaining the statistically significant parameters and their percentage contribution.
4. High-impact journal publications and the filing of the patent.

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